Nucleosynthesis and mixing in the first generations of low- and intermediate-mass

Falk Herwig

Keele University, UK

Collaborators:
Paul Woodward (LCSE)
Frank Timmes (LANL/ASU)
David Porter (LCSE)
Bernd Freytag (Lyon)
Robert Hueckstaedt (LANL)
Chris Fryer (LANL)
Mixing processes in metal-poor stars

We have seen yesterday: rotation is important at extremely low and zero metallicity (Meynet, Ekstrom, Yoon, Chiappini and others).

The other recurring theme in EMP/Z=0 stars are convective-reactive episodes involving H-rich unprocessed and He-burning (=\(^{12}\)C rich) material.

The common feature is that in one or another way \(H\) is mixed with primary \(^{12}\)C from He-core or -shell burning leading to violent, often runaway flash burning, often with irreversible and significant consequences for the subsequent evolution and eventually nuclear yields.
Mixing processes in metal-poor stars

The convective-reactive events occur favorably at $Z=0$ or extremely low metallicity:

- the entropy barrier between H- and He-shell is low
- H-rich material is initially extremely metal- (=C-)poor

If the H/$^{12}$C convective-reactive event happens we produce $^{13}$C and $^{14}$N, the latter of which may eventually end up as $^{22}$Ne and serve as neutron source, or to enhance neutronization.
This conference:

- Stan Woosley mentioned in passing convective-reactive event when speculating how a $200\text{M}_{\odot}$ PopIII star could become a red giant
- Takuma Suda mentioned He-FDDM (He-flash driven deep mixing)
- Simon Campbell (later today): He-core flash and He-shell flash H-ingestion events (PIE = proton-ingestion episodes)
More examples

More examples:
5Msun, Z=0

Upper panel:
Top of He-shell flash convection zone has just started a H-flash after H-ingestion.

Bottom panel:
Convective diffusion coefficient with mixing model for the boundary.

(2002 St Luc CNO meeting)
More examples:
5Msun, Z=0

Upper panel:
Top of He-shell flash convection zone has just started a H-flash after H-ingestion.

Bottom panel:
Convective diffusion coefficient with mixing model for the boundary.

(2002 St Luc CNO meeting)
Another variant of convective-reactive events at EMP and below: The hot dredge-up

- Even tiny amounts of mixing of H from the unstable envelope into the hot $^{12}$C-rich core:
  - Corrosive H-flame burning
  - Details of convective-reactive event determine the dredge-up BIG TIME!

Herwig 2004.
Goriely & Siess, 2004
More examples from solar metallicity

- "final flash" post-AGB stars
- Delayed He-core flash
- Accreting white dwarfs and neutron stars

Sakurai’s object

VLA image

Hadjuk et al., Science 2005
Hydrodynamics of He-shell flash convection

- Initial conditions: piecewise polytropic stratification with gravity that closely resembles the actual conditions in a specific \(2M_\odot\), \(Z=0.01\) thermal pulse model

Initial setup

Comparison of T-profile of initial stratification for hydro simulation and from full 1D stellar evolution model using MLT.

- Constant volume heating at bottom of unstable layer, corresponding to He-burning luminosity

Vertical entropy profile of initial setup for hydro simulation.
Stellar interior convection:
Hydrodynamics and Mixing of He-shell Flash Convection

lc0gh:  time=4300 s  \( v_{\text{rms, max}} = 16.2 \text{ km/s} \)

Pressure fluctuations with pseudo-streamlines overplotted, 2D, 1200x400, enhanced heating (30x) (lc0gh)
Stellar interior convection:
Hydrodynamics and Mixing of He-shell Flash Convection

lc0gi: time=4000 s \( v_{\text{Ams, max}} = 14.4 \text{ km/s} \)

Entropy fluctuations, 2D, 2400x800, realistic heating (lc0gi)
New code:
PPM slow-flow perturbation version for stellar interior hydrodynamics and nuclear burn (Paul Woodward, LCSE@U Minnesota).

He-shell flash convection
Vertical velocity 512x64x512
4k CPU hrs
New code:
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He-shell flash convection
Vertical velocity 512x512x256
Now - with some idea of the global properties of this convection zone - let's put in multiple fluids and nuclear burning

The H-ingestion flash - H-ingestion into the He-shell flash

Disclaimer: The following simulation is wrong in 2D and especially the boundaries are unresolved! This is just an instructive exploration ...

However, as always in simulations we should aim to solve the right equations for the problem and to solve the equations right. In the following 2D simulations we solve the right equations wrong (under-resolved and in 2D instead of 3D), whereas in the 1D diffusion approximation of the problem within stellar evolution codes we solve the wrong equations right (convective mixing of entrained H in the He-shell flash convection zone is not a diffusion process).
H-ingestion He-shell flash convection simulation, realistic stratification, realistic burn, 4 fluids with realistic mol weights.
Let's see if we can simulate the top boundary of the convection zone -> Woodward's talk

T-profile of initial stratification for hydro simulation and from full 1D stellar evolution model using MLT. Woodward's simulations will show the entrainment at the top 200km (red shaded zone) around the top convective boundary with a velocity perturbation pattern emulating the global convection simulations.